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Project: BTeV Straws

Title: Discussion of Straw Sag and Frame Load Analyses

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Abstract Summary: The inter-relationship of straw load and sag of straw frame design and deflection is discussed. Document summarizes the effect of axial tension on straw form and explores the influence of temperature and humidity on tension for various assembly possibilities. Also, the load requirements of the straw frames is discussed.

Applicable Codes:

Discussion of Straw Gravitational Sag and Frame Loads Analyses

BTeV Document 3978
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Introduction

Design of the Straw Tracker's station frames requires an understanding of the tensile loads the straws exert on the frame. Straw straightness depends on carefully developed assembly procedures and gravitational load conditions. For straws with lateral gravitational loads, straightness is improved to some extent by tensioning the straws. Axial tensile loads in the straws are generated by intentionally stretching straws as they are installed into the frames. The resulting straw load is affected by this initial mechanical strain; and since the straws are fabricated principally of polymers, temperature and humidity changes and time-dependent creep also have an influence. For these reasons, loads on the frames are transient and transient loads in the straws may impact their position stability. This document summarizes the effect of axial tension on straw form and explores the influence of temperature and humidity on tension for various assembly possibilities. Finally, the load requirements of the straw frames are discussed.

Straw Tracker Overview

The full Straw Tracker is an assembly of seven stations and each station includes an X, V, and U-view. The designs of Stations 1-6 are very similar while Station 7's design is different because its size would otherwise be impossible to install.

A rendering of the Station 3 prototype half-view frame is shown in Figure 1. Each of Station 3's half-view frames includes nine Straw Modules. A module is a subassembly of straws. The module construction is shown in Figure 2. Each module has (48) straws, with the exception of those that are adjacent to the accelerator's beam-pipe. This module type is called Module Zero and it holds (46) straws. Modules include straws, wire centering devices fixed inside the straws (called twisters), straw end plugs, and end plates. The straws and end plugs are glued into the end plates. The end plates are aligned to the station frames with dowel pins and anchored with fasteners.

A (48)-straw module type occupies each of module positions 1 through 9 on the Station 3 frame. Two shorter modules of the 'Module Zero' type occupy the Module Zero position of the frame, since the plane of straws has to be cut in that region to accommodate the beam pipe.

The frame is stiffened in the Module One position by the addition of a carbon fiber reinforced epoxy (CFRE) strut that sleeves over the straw module.

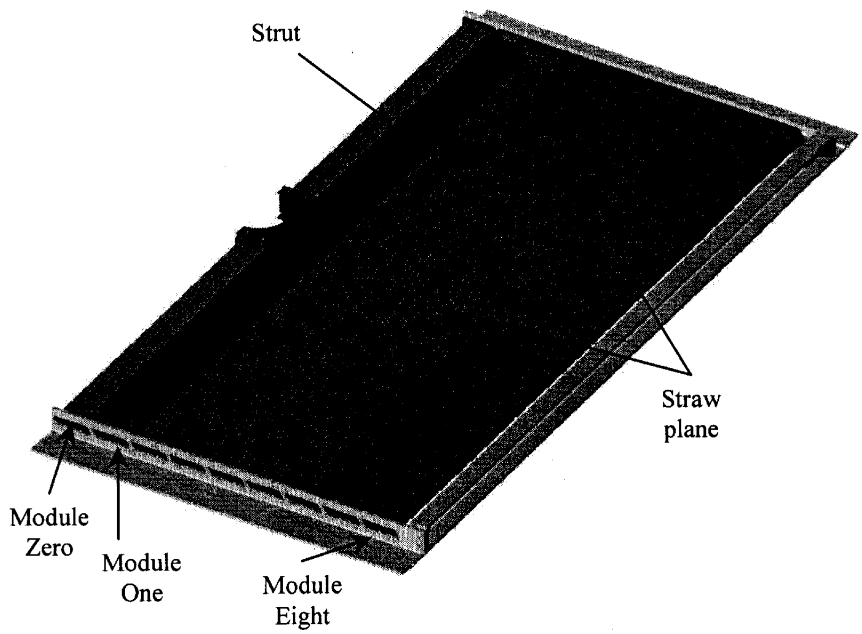

Figure 1 - Station 3 prototype half-view frame

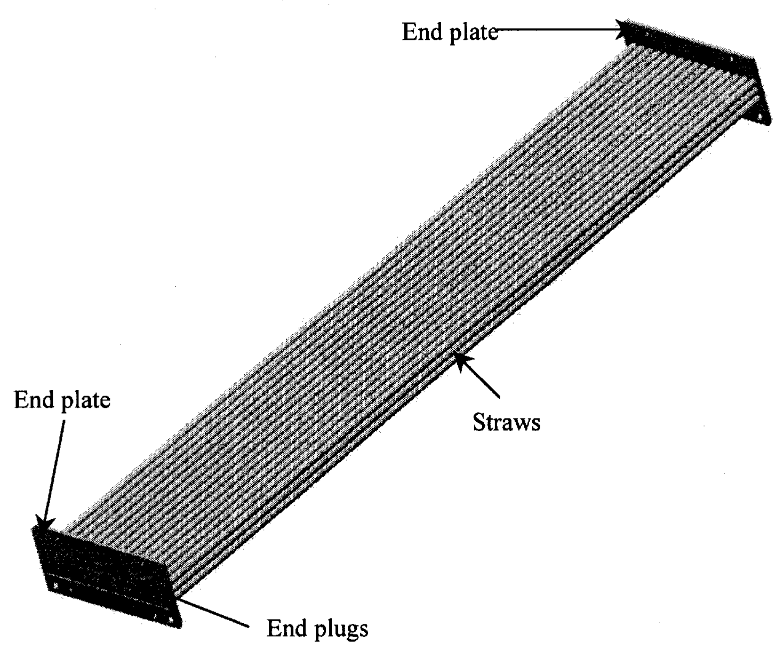

Figure 2 - Straw module

Straw Properties and Analyses Discussion

The final design of the straw has not been fixed. The decisions of material type and straw wall thickness are still open. The table below summarizes the two candidate material types and their important mechanical properties.

Table 1 Material properties

Material Type	Modulus [PSI]	CTE [1/C]	CME [1/%RH]
Kapton	3.7×10^5	2.2×10^{-5}	2.0×10^{-5}
Mylar	7.1×10^5	1.7×10^{-5}	6.0×10^{-5}

This document assumes straws have a 4mm internal diameter. This is the baseline diameter of the straw but a 8mm straw version is being considered for regions of high occupancy. Analysis for the 8mm straw is not included here.

The design of Station 7 has not passed a conceptual phase. The discussion of this document is for the module design used in Station 1-6. Calculations are also presented for modules of Station 7 length, but assuming the current module design for Stations 1-6. The modules in Station 7 may or may not include groupings of (48) straws.

The straws in the X-view run vertically. The straws in the U and V-views are +/-11.2° from horizontal and their straightness is therefore affected by gravitational pull. The gravitational sag analyses in this document assume straws are completely horizontal. The analyses for gravitational sag with axial tension is done as described in Roark and Young, 7th Edition, Table 8.9, Formulas for Beams Under Simultaneous Axial Tension and Transverse Loading, both ends fixed with a lateral distributed load (case 2d).

Single Straw Analysis of Gravitational Sag

The current thinking is to bundle straws within a single module so that they act together as a composite unit. The analysis presented in this section is for single straws only. The results, when compared to the analysis in the next section for straws bundled within a module, show the motivation for straw bundling.

Table 2 - Single straw gravitational sag versus length and axial tension

4mm straw, 2mil wall, Kapton

Straw Length		Maximum Sag [mm] with Axial Load [g]				
[cm]	[in]	P = 0g	P = 100g	P = 150g	P = 200g	P = 250g
12.7	5	0.00	0.00	0.00	0.00	0.00
25.4	10	-0.03	-0.02	-0.02	-0.02	-0.01
38.1	15	-0.14	-0.07	-0.06	-0.05	-0.04
50.8	20	-0.45	-0.16	-0.12	-0.10	-0.08
63.5	25	-1.09	-0.29	-0.22	-0.17	-0.14
76.2	30	-2.23	-0.46	-0.33	-0.26	-0.22
88.9	35	-4.07	-0.67	-0.47	-0.37	-0.30
101.6	40	-6.83	-0.91	-0.64	-0.50	-0.41
114.3	45	-10.75	-1.19	-0.83	-0.64	-0.55
127.0	50	-16.06	-1.51	-1.05	-0.82	-3.82

4mm straw, 1mil wall, Kapton

Straw Length		Maximum Sag [mm] with Axial Load [g]				
[cm]	[in]	P = 0g	P = 100g	P = 150g	P = 200g	P = 250g
12.7	5	0.00	0.00	0.00	0.00	0.00
25.4	10	-0.03	-0.02	-0.01	-0.01	-0.01
38.1	15	-0.14	-0.05	-0.04	-0.03	-0.02
50.8	20	-0.45	-0.10	-0.07	-0.06	-0.05
63.5	25	-1.07	-0.17	-0.12	-0.09	-0.08
76.2	30	-2.17	-0.26	-0.18	-0.14	-0.11
88.9	35	-3.91	-0.37	-0.26	-0.20	0.00
101.6	40	-6.46	-0.49	-0.34	0.00	0.00
114.3	45	-10.00	-0.64	-0.42	0.00	0.00
127.0	50	-14.69	-0.83	0.00	0.00	0.00

4mm straw, 2mil wall, Mylar

Straw Length		Maximum Sag [mm] with Axial Load [g]				
[cm]	[in]	P = 0g	P = 100g	P = 150g	P = 200g	P = 250g
12.7	5	0.00	0.00	0.00	0.00	0.00
25.4	10	-0.02	-0.01	-0.01	-0.01	-0.01
38.1	15	-0.07	-0.05	-0.04	-0.04	-0.03
50.8	20	-0.23	-0.12	-0.10	-0.08	-0.07
63.5	25	-0.56	-0.23	-0.18	-0.14	-0.12
76.2	30	-1.16	-0.38	-0.28	-0.23	-0.19
88.9	35	-2.13	-0.57	-0.42	-0.33	-0.27
101.6	40	-3.60	-0.79	-0.57	-0.45	-0.37
114.3	45	-5.72	-1.05	-0.75	-0.59	-0.48
127.0	50	-8.62	-1.35	-0.96	-0.74	-0.61

4mm straw, 1mil wall, Mylar

Straw Length		Maximum Sag [mm] with Axial Load [g]				
[cm]	[in]	P = 0g	P = 100g	P = 150g	P = 200g	P = 250g
12.7	5	0.00	0.00	0.00	0.00	0.00
25.4	10	-0.02	-0.01	-0.01	-0.01	-0.01
38.1	15	-0.07	-0.04	-0.03	-0.02	-0.02
50.8	20	-0.23	-0.08	-0.06	-0.05	-0.04
63.5	25	-0.56	-0.14	-0.11	-0.08	-0.07
76.2	30	-1.15	-0.23	-0.16	-0.13	-0.10
88.9	35	-2.10	-0.33	-0.23	-0.18	-0.15
101.6	40	-3.51	-0.45	-0.31	-0.24	-0.20
114.3	45	-5.52	-0.58	-0.41	-0.31	-0.26
127.0	50	-8.24	-0.74	-0.51	-0.46	0.00

Bundled Module Analysis of Gravitational Sag

This section assumes adjacent straws within a module are glued to each other so that the straws act together as a composite. The distributed lateral load of the module includes the straws plus some epoxy. The epoxy is assumed to weigh 6.169×10^{-4} lbs/inch, or 25% of the weight of straws with 2mil wall thickness. This is a conservative assumption.

Table 3 - Moment of inertia of bundled modules

Straw wall thickness [in]	Moment of Inertia [in^4]	
	16-straw direction	3-straw direction
.001	.01380	3.938×10^{-4}
.002	.02778	7.945×10^{-4}

Table 4 shows the sag for a bundled straw module at its mid-length. Sag is calculated for zero to 200 grams/straw of axial load for module lengths for Stations 2 through 7. Results for Station 1 are not included since the calculated sag for such short modules is effectively zero. If epoxy loading were ignored, the sag of the module with 2mil straws would be the same as those with 1mil straws. This is because the moment of inertia increases by 2x going from 1mil to 2mils but the distributed weight of the straws also increases 2x. These effects cancel each other out. But since the same mass of epoxy is assumed in both module types, the 1mil bundle has slightly higher sag values.

Looking at the results for the 127cm long straws in both Table 2 and Table 3 illustrates one motivation for bundling of straws within a module. The calculated sag with 200g axial tension for a single 127cm long Kapton straw with 2mil wall is 0.82mm. A bundled module of the same straws with the same axial load per straw has a 0.11mm sag, a reduction greater than 7:1. For lower axial tension values the relative reduction in sag is greater, better than 100:1 for the case of zero axial load.

There is not yet a requirement for total sag permitted across a straw. A criterion might be selected based on allowable deviation of the anode wire from the straw's centerline to limit the risk of electrostatic forces causing the wire to snap over to the cathode of the straw. The spacing of wire centering devices in the straw and tolerances on straw internal diameter, straw form, and twister geometry might all be considered to develop this number. Without that analysis, however, 0.4mm maximum sag seems like a reasonable ceiling for the value. Table 4 shows then that modules up to Station 3 or 4 length may be self supporting but that other mechanisms will need to be employed to maintain straw straightness in longer modules.

Table 5 shows the results in Table 4 normalized to the zero axial load condition to illustrate the effect of axial tension on sag for bundled modules. Table 5 shows that in the range of reasonable allowable sag values, tension has a 10 to 20% effect on sag. It shows that for bundled modules, high tension values weakly control straw form. The tables can also be studied, with consideration of the strain effects (both positive and negative) that creep, temperature, and humidity may have on straw position stability. More discussion on this topic follows.

Table 4 - Module Sag [mm] v. Straw Length and Axial Load, P [g/straw]

4mm straw, 2mil wall, Kapton, (48) straw module

Station	Length [cm]	Maximum sag [mm] with Axial Load [g/straw]				
		P = 0g	P = 50g	P = 100g	P = 150g	P = 200g
2	89	-0.03	-0.03	-0.03	-0.03	-0.03
3	127	-0.12	-0.12	-0.12	-0.11	-0.11
4	180	-0.50	-0.47	-0.45	-0.42	-0.40
5	208	-0.90	-0.83	-0.77	-0.71	-0.67
6	236	-1.48	-1.34	-1.22	-1.11	-1.03
7	411	-13.58	-10.23	-8.18	-6.83	-5.86

4mm straw, 1mil wall, Kapton, (48) straw module

Station	Length [cm]	Maximum sag [mm] with Axial Load [g/straw]				
		P = 0g	P = 50g	P = 100g	P = 150g	P = 200g
2	89	-0.04	-0.03	-0.03	-0.03	-0.03
3	127	-0.15	-0.14	-0.13	-0.12	-0.12
4	180	-0.61	-0.54	-0.48	-0.44	-0.40
5	208	-1.08	-0.92	-0.80	-0.71	-0.64
6	236	-1.78	-1.46	-1.24	-1.07	-0.95
7	411	-16.22	-9.82	-7.02	-5.48	-4.50

4mm straw, 2mil wall, Mylar, (48) straw module

Station	Length [cm]	Maximum sag [mm] with Axial Load [g/straw]				
		P = 0g	P = 50g	P = 100g	P = 150g	P = 200g
2	89	-0.02	-0.02	-0.01	-0.01	-0.01
3	127	-0.06	-0.06	-0.06	-0.06	-0.06
4	180	-0.26	-0.25	-0.24	-0.23	-0.23
5	208	-0.46	-0.44	-0.42	-0.40	-0.39
6	236	-0.76	-0.72	-0.68	-0.65	-0.62
7	411	-6.98	-5.96	-5.18	-4.59	-4.12

4mm straw, 1mil wall, Mylar (48) straw module

Station	Length [cm]	Maximum sag [mm] with Axial Load [g/straw]				
		P = 0g	P = 50g	P = 100g	P = 150g	P = 200g
2	89	-0.02	-0.02	-0.02	-0.02	-0.02
3	127	-0.08	-0.07	-0.07	-0.07	-0.07
4	180	-0.31	-0.29	-0.27	-0.26	-0.25
5	208	-0.55	-0.51	-0.47	-0.44	-0.41
6	236	-0.92	-0.82	-0.74	-0.68	-0.63
7	411	-8.39	-6.24	-4.96	-4.12	-3.52

Table 5 - Module Sag [Δ%] v. Straw Length and Axial Load, P [g/straw]

4mm straw, 2mil wall, Kapton, (48) straw module

Station	Length [cm]	Maximum sag [Δ%] with Axial Load [g/straw]				
		P = 0g	P = 50g	P = 100g	P = 150g	P = 200g
2	89	-	-2%	-3%	-4%	-6%
3	127	-	-3%	-6%	-9%	-11%
4	180	-	-6%	-11%	-16%	-20%
5	208	-	-8%	-15%	-20%	-26%
6	236	-	-10%	-18%	-25%	-31%
7	411	-	-25%	-40%	-50%	-57%

4mm straw, 1mil wall, Kapton, (48) straw module

Station	Length [cm]	Maximum sag [Δ%] with Axial Load [g/straw]				
		P = 0g	P = 50g	P = 100g	P = 150g	P = 200g
2	89	-	-3%	-6%	-9%	-11%
3	127	-	-6%	-11%	-16%	-20%
4	180	-	-11%	-20%	-28%	-34%
5	208	-	-15%	-25%	-34%	-41%
6	236	-	-18%	-31%	-40%	-47%
7	411	-	-39%	-57%	-66%	-72%

4mm straw, 2mil wall, Mylar, (48) straw module

Station	Length [cm]	Maximum sag [Δ%] with Axial Load [g/straw]				
		P = 0g	P = 50g	P = 100g	P = 150g	P = 200g
2	89	-	0%	-2%	-2%	-3%
3	127	-	-2%	-3%	-5%	-6%
4	180	-	-3%	-6%	-9%	-12%
5	208	-	-4%	-8%	-12%	-15%
6	236	-	-5%	-10%	-15%	-19%
7	411	-	-15%	-26%	-34%	-41%

4mm straw, 1mil wall, Mylar (48) straw module

Station	Length [cm]	Maximum sag [Δ%] with Axial Load [g/straw]				
		P = 0g	P = 50g	P = 100g	P = 150g	P = 200g
2	89	-	-1%	-3%	-4%	-6%
3	127	-	-3%	-6%	-9%	-12%
4	180	-	-6%	-12%	-17%	-21%
5	208	-	-8%	-15%	-21%	-26%
6	236	-	-10%	-19%	-26%	-32%
7	411	-	-26%	-41%	-51%	-58%

Other Considerations for Stiffening Straws

There are ways to further stiffen straw modules to resist gravitational sag and stabilize them against the transients of creep, temperature, and humidity. One idea is to add carbon fiber reinforcement to the modules. Another approach would be to connect modules to each other after they are installed in the frame. By this method, the composite 48-straw beam of a single module is built successively larger (and stiffer) by joining neighboring modules to each other.

<u>CFRE Rod Reinforcements</u>

The ATLAS straw detector group used carbon fiber reinforced epoxy (CFRE) to stiffen their straws against gravitational sag and to constrain each straw against thermal and humidity effects. Four carbon fiber rods were attached along each straw length to its outside diameter at every 90°. The method is described in the ATLAS Inner Detector TDR.

The BTeV straw detector differs from the ATLAS detector in that the BTeV straws are close-packed. The 4mm ATLAS straws are spaced on a 6.8mm pitch. The close packing of BTeV straws simplifies module bundling and still allows installation of carbon fiber reinforcements in the voids of neighboring straws. For stiffening straws to resist gravitational sag, the number and placement of CFRE filaments can be selected to achieve maximum allowable sag targets. For example, four 0.5mm CFRE rods glued into a 180cm long (Sta4) module (1mil wall, Kapton) are enough to reduce sag from 0.61mm to 0.12mm (no axial tension). Figure 3 shows the assumed location of the rods for this calculation.

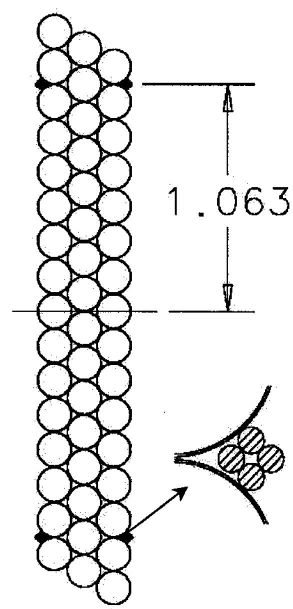

Figure 3 - CFRE rods stiffen module

Table 6 shows the results of a series of calculations for module sag versus number of CFRE rods used, axial tension, and module length. Note that as the 'beam' is stiffened by more rods, the effect of axial load on sag is more and more diminished. For these calculations, all rods are assumed to be installed at d = 1.063"/2.70cm from the center axis of the module. Figure 3 shows the case of a total of (16) rods in a module.

The reinforcements added as described here stiffen the module as shown in Table 6 against the forces or gravitational sag. It is not clear what influence, if any, this sparing use of reinforcements would have on thermal and moisture strains expected from ambient changes. Installation of a single rod in each of the (30) voids between the straws might create a more robust module that is both rigid in gravity and self-constrained against humidity and temperature effects. Although the additional mass of these fibers would have to be considered, the larger issue may be the assembly technique. Rods as shown in

Figure 3 can be readily added after modules are installed (and stretched) into the frames. In this way, the loads of module pre-stretch are a result of straining only the straws. But if modules were reinforced before installing them into the frames, loads to pre-stretch the straws and reinforcements would be very large.

A technical data sheet of the CFRE rods assumed for these calculations is included in the appendix. Modulus of the rods is calculated by multiplying fiber volume and fiber tensile modulus: 0.62 x 33 MSI = 20.5 MSI. It should be noted that this is a relatively low modulus fiber.

Joining of Multiple Modules

A low mass coupling of modules in a frame is another possible technique towards reducing gravitational sag and the effect of creep and ambient temperature and humidity on straw stability. When installed in the frames, the space between adjacent modules is approximately one straw diameter. Joining adjacent modules results in much taller beams in the direction of gravitational load for the U and V-views, reducing the resultant sag. Table 7 summarizes sag results of parametric calculations for 2 to 8 modules. Gravitational sag for a single module is also included for comparison. The calculations assume zero axial tension.

Table 6 – Module sag [mm] v. length, axial load, and number of CFRE rod reinforcements

4mm straw, 2mil wall, Kapton, (48) straw module

Station Number	Module Length [mm]	Maximum sag [mm] v. #of CFRE Rods, Axial Load, and Length							
		4 CFRE rods		8 CFRE rods		12 CFRE rods		16 CFRE rods	
		P=0g	P=200g	P=0g	P=200g	P=0g	P=200g	P=0g	P=200g
2	88.9	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00
3	127.0	-0.03	-0.03	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01
4	180.3	-0.13	-0.13	-0.08	-0.08	-0.06	-0.06	-0.04	-0.04
5	208.3	-0.24	-0.22	-0.14	-0.13	-0.10	-0.10	-0.08	-0.08
6	236.2	-0.40	-0.35	-0.23	-0.22	-0.17	-0.16	-0.13	-0.13
7	411.5	-3.64	-2.70	-2.14	-1.78	-1.53	-1.34	-1.21	-1.09

4mm straw, 1mil wall, Kapton, (48) straw module

Station Number	Module Length [mm]	Maximum sag [mm] v. #of CFRE Rods, Axial Load, and Length							
		4 CFRE rods		8 CFRE rods		12 CFRE rods		16 CFRE rods	
		P=0g	P=200g	P=0g	P=200g	P=0g	P=200g	P=0g	P=200g
2	88.9	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00
3	127.0	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
4	180.3	-0.09	-0.09	-0.05	-0.05	-0.04	-0.04	-0.03	-0.03
5	208.3	-0.17	-0.15	-0.09	-0.09	-0.07	-0.06	-0.05	-0.05
6	236.2	-0.28	-0.24	-0.15	-0.14	-0.11	-0.10	-0.09	-0.08
7	411.5	-2.54	-1.81	-1.42	-1.17	-1.01	-0.88	-0.79	-0.71

4mm straw, 2mil wall, Mylar, (48) straw module

Station Number	Module Length [mm]	Maximum sag [mm] v. #of CFRE Rods, Axial Load, and Length							
		4 CFRE rods		8 CFRE rods		12 CFRE rods		16 CFRE rods	
		P=0g	P=200g	P=0g	P=200g	P=0g	P=200g	P=0g	P=200g
2	88.9	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00
3	127.0	-0.03	-0.03	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01
4	180.3	-0.11	-0.10	-0.07	-0.07	-0.05	-0.05	-0.04	-0.04
5	208.3	-0.19	-0.18	-0.12	-0.12	-0.09	-0.09	-0.07	-0.07
6	236.2	-0.31	-0.29	-0.20	-0.19	-0.15	-0.14	-0.12	-0.12
7	411.5	-2.89	-2.25	-1.85	-1.57	-1.38	-1.22	-1.10	-1.00

4mm straw, 1mil wall, Mylar, (48) straw module

Station Number	Module Length [mm]	Maximum sag [mm] v. #of CFRE Rods, Axial Load, and Length							
		4 CFRE rods		8 CFRE rods		12 CFRE rods		16 CFRE rods	
		P=0g	P=200g	P=0g	P=200g	P=0g	P=200g	P=0g	P=200g
2	88.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	127.0	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
4	180.3	-0.08	-0.08	-0.05	-0.05	-0.04	-0.03	-0.03	-0.03
5	208.3	-0.14	-0.13	-0.09	-0.08	-0.06	-0.06	-0.05	-0.05
6	236.2	-0.24	-0.21	-0.14	-0.13	-0.10	-0.10	-0.08	-0.08
7	411.5	-2.20	-1.63	-1.31	-1.09	-0.95	-0.83	-0.75	-0.68

Table 7 - Gravitational sag [mm] with coupling of multiple modules

4mm straw, 2mil wall, Kapton, (48) straw module

Station	Length [cm]	Module Sag [mm] v. L and # of Modules			
		1 module	2 modules	4 modules	8 modules
2	88.9	0.03	0.01	0.00	0.00
3	127.0	0.12	0.03	0.01	0.00
4	180.3	0.50	0.13	0.06	0.01
5	208.3	0.90	0.23	0.10	0.01
6	236.2	1.49	0.37	0.17	0.02
7	411.5	13.67	3.44	1.52	0.20

4mm straw, 1mil wall, Kapton, (48) straw module

Station	Length [cm]	Module Sag [mm] v. L and # of Modules			
		1 module	2 modules	4 modules	8 modules
2	88.9	0.04	0.01	0.00	0.00
3	127.0	0.15	0.04	0.02	0.00
4	180.3	0.61	0.15	0.07	0.01
5	208.3	1.08	0.27	0.12	0.02
6	236.2	1.79	0.45	0.20	0.03
7	411.5	16.44	4.14	1.83	0.24

4mm straw, 2mil wall, Mylar, (48) straw module

Station	Length [cm]	Module Sag [mm] v. L and # of Modules			
		1 module	2 modules	4 modules	8 modules
2	88.9	0.02	0.00	0.00	0.00
3	127.0	0.06	0.02	0.01	0.00
4	180.3	0.26	0.07	0.03	0.00
5	208.3	0.47	0.12	0.05	0.01
6	236.2	0.77	0.19	0.09	0.01
7	411.5	7.13	1.79	0.79	0.10

4mm straw, 1mil wall, Mylar, (48) straw module

Station	Length [cm]	Module Sag [mm] v. L and # of Modules			
		1 module	2 modules	4 modules	8 modules
2	88.9	0.02	0.00	0.00	0.00
3	127.0	0.08	0.02	0.01	0.00
4	180.3	0.32	0.08	0.04	0.00
5	208.3	0.56	0.14	0.06	0.01
6	236.2	0.93	0.23	0.10	0.01
7	411.5	8.57	2.16	0.95	0.12

Loads on Frames

Straw loads on the frames result from the combined effects of straw pre-tension, thermal and moisture loads, and creep. A straw's free length will increase with increases in straw temperature or moisture content. For modules already installed in the frames, this growth in free length is restrained. The effect instead is first a reduction in existing straw tension and then the possibility of developing compressive loads in the straws. Decreasing temperature and moisture content will increase straw tension and frame loads. The previous sections have shown the inter-relationship between gravitational sag of straws in U and V-views and axial tension. In general, increasing tension reduces sag. Transient thermal and moisture loads as well as creep have the potential to have a transient effect on channel position.

The previous calculations show that as straws are combined and reinforced into stiffer groupings, the relationship between gravitational sag and tension is weakened. One goal then in the development of straw and half-view assembly techniques may be to stiffen straws to a level where tensile load transients have limited impact on straw position resolution. Achieving this may also accomplish a corollary goal: a divorce in the relationship between straw straightness and tension. The exception may be that care needs to be taken to avoid buckling of straws out of plane due to compressive loads that may result from environmental conditions. Analyses can be done to try to develop a method to avoid compressive loads or to avoid compressive levels that result in buckling. But it may be shown that it is operationally very difficult to develop a system that is robust enough that this is guaranteed not to happen. Instead, it may be sufficient, if straws can survive cycles through compressive forces, to develop procedures that accommodate extreme incursions of ambient conditions from normal operational bands.

Module and half-view assembly techniques have yet to be developed and the robustness of such assemblies has yet to be tested. Until then, a reasonable best guess analysis needs to be done to move forward on frame design. The following paragraphs describe the thinking and resultant mechanical loads that half-view frames will be expected to accommodate.

When installing modules into the frames, it is important that module length not exceed the length of the frame to avoid risk of damaging the straws when trying to force a fit. For this reason, station frame length will be controlled to a nominal dimension with tolerances adding to length and module length will be controlled to some nominal with tolerances subtracting from nominal. Additionally, the nominal length of the module will be selected so that it is smaller than the nominal length of the frame. This is to allow enough pre-stretch on the straws to accommodate reasonable excursions of ambient conditions and creep relaxation as chambers age.

The table below shows the nominal station dimensions, some best estimate on reasonable tolerances of assembly, and resultant loads with straw stretch of 0.1% strain. Modules are assumed to be fabricated at 40%RH and 20C. Operating conditions as installed in the frame assumed to be 0%RH and 15C.

Table 8 - Load per straw [g] for frames with $\Delta RH = -40\%$ and $\Delta T = -5C$

Station	1	2	3	4	5	6	7
Frame Tolerance [in]	0.010	0.010	0.020	0.020	0.020	0.020	0.020
Module Tolerance [in]	0.005	0.005	0.010	0.010	0.010	0.010	0.020
Minimum Stretch [in]*	0.024	0.035	0.050	0.071	0.082	0.093	0.162
Total Stretch [in]	0.039	0.050	0.080	0.101	0.112	0.123	0.202
Frame Length [in]	24.0	35.0	50.0	71.0	82.0	93.0	162.0
Module Length [in]	23.961	34.95	49.92	70.899	81.888	92.877	161.798
Strain from stretch	0.00163	0.00143	0.00160	0.00142	0.00137	0.00132	0.00125
Strain from dRH - Kapton	0.00088	0.00088	0.00088	0.00088	0.00088	0.00088	0.00088
Strain from dT - Kapton	0.00010	0.00010	0.00010	0.00010	0.00010	0.00010	0.00010
Total Strain - Kapton	**0.00261**	**0.00241**	**0.00258**	**0.00240**	**0.00235**	**0.00230**	**0.00223**
Strain from dRH - Mylar	0.00024	0.00024	0.00024	0.00024	0.00024	0.00024	0.00024
Strain from dT - Mylar	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009
Total Strain - Mylar	**0.0019**	**0.0017**	**0.0018**	**0.0017**	**0.0016**	**0.0016**	**0.0015**

Kapton-1mil	Loads [g/straw]						
Pre-Load	137	120	134	120	115	111	105
RH Load	74	74	74	74	74	74	74
Temp. Load	8	8	8	8	8	8	8
Total Load/straw	**219**	**202**	**217**	**202**	**197**	**193**	**187**
Straw Stress [psi]	**199**	**184**	**197**	**184**	**179**	**176**	**170**

Kapton-2mil	Loads [g/straw]						
Pre-Load	275	242	271	241	231	224	211
RH Load	149	149	149	149	149	149	149
Temp. Load	17	17	17	17	17	17	17
Total Load/straw	**440**	**407**	**436**	**406**	**396**	**389**	**376**
Straw Stress [psi]	**199**	**184**	**197**	**184**	**179**	**176**	**170**

Mylar-1mil	Loads [g/straw]						
Pre-Load	262	230	258	229	220	213	201
RH Load	39	39	39	39	39	39	39
Temp. Load	14	14	14	14	14	14	14
Total Load/straw	**314**	**283**	**310**	**282**	**273**	**266**	**253**
Straw Stress [psi]	**286**	**258**	**283**	**257**	**248**	**242**	**231**

Mylar-2mil	Loads [g/straw]						
Pre-Load	527	464	519	462	443	429	405
RH Load	78	78	78	78	78	78	78
Temp. Load	28	28	28	28	28	28	28
Total Load/straw	**633**	**569**	**625**	**567**	**549**	**534**	**510**
Straw Stress [psi]	**286**	**258**	**283**	**257**	**248**	**242**	**231**

*Assumed pre-stretch = 0.1% strain

Appendix

Technical Data sheet on CFRE rods assumed for reinforced modules.

Grade: GR-CFR

Manufacturer:	Graphtek LLC
Description:	Manufactured by pulling carbon fiber and vinylester through a die of the desired cross section to form a densely reinforced carbon composite to provide excellent tensile, compressive, and transverse strength.

PROPERTY	US VALUE		METRIC VALUE	
Resin	**Vinylester**			
Fiber Type	**33 m.s.i. Carbon**			
Composite Type	**Unidirectional Orientation**			
Tensile Strength	**200000**	psi	**1379.0**	mpa
Flexural Strength	**230000**	psi	**1585.8**	mpa
Flexural Modulus	**17.8**	m.s.i.		
Shear Strength	**9500**	psi	**65.5**	mpa
Fiber volume	**62**	%		
Density	**.054**	lb/in ^{3}	**1.49**	gr/cm ^{3}
Diameter Tolerance	**+.003 / -.003**	in	**+.008 / -.008**	cm